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Serge J.A. Bierhuizen

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51.5: Single Panel Color Sequential Projectors with Polarization Recovery

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Abstract

Color sequential single panel LCD projectors potentially fulfill the need for low cost projection systems. This paper describes and compares potential alternative and integrated solutions for cost drivers like polarization and color recovery.

1. Introduction

Further cost reduction of projection engines, both front and rear, is required to reach the consumer price range. Lower cost through miniaturization of the light valves has been the trend in the past years. In addition, new, fast switching LCD and LCOS panels are being developed, which enable low cost single panel color sequential projection systems.

For this study we investigated comparatively simpler, less expensive color sequential alternatives instead of scrolling prism architectures [13]. Looking at the cost breakdown of the engine, the polarization conversion optics take up about 20% of the total optical component cost and was therefore one of the items that was focused on. Several architectures were designed, simulated or prototyped. Although performance is low initially, single panel LCOS may become a disruptive technology as described by C. Christensen in 'The Innovator's Dilemma' [3].

2. Color Switch Architecture

A typical color sequential architecture is shown in Figure 1 and consists of a short arc mercury lamp [10], integration optics for homogenizing the beam at the panel [2], a polarization conversion array [9], illumination lenses, a Color Switch [1] [12], a polarizing beam splitter (PBS), a single panel imager and a projection lens.

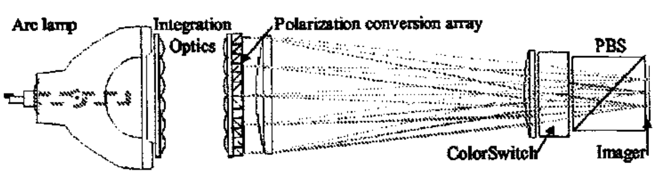

Figure 1. Typical architecture of single panel LCOS

The collection of light (ϕ) from an UHP lamp with power (P) and arc-length (d) can be approximated by [10]

$$\phi_{[lm]} = 32 \cdot P_{[W]} \cdot \tan^{-1}\left(\frac{E_{[mm^2 \cdot sr]}}{3.8 \cdot d^2 + 0.9 \cdot d - 0.8}\right) \text{ and } E_{system} = \frac{\pi \cdot A_{ill}}{(2 * F_{\#})^2}$$

where E is the étendue or optical extent of the light collection system, d is the arc gap between the electrodes (e.g. 1.0 mm) and A_{ill} is the illuminated display area with the $F_{\#}$ of the projection lens. In projection systems with a PCS (Polarization Conversion System, where unpolarized light from the light source is converted into the required linearly polarized light) the étendue of the light collected from the lamp is approximately half of the system étendue as a typical PCS doubles the étendue of the beam [14].

This basic relationship does not hold true for more exotic polarization conversion schemes such as those that involve recirculation through the lamp arc [11]. However, in that case some light may be absorbed at the arc electrodes and potentially reduce the lifetime.

The total system output can be calculated with [14]

$$\phi_{out} = \phi_{lamp} \cdot \prod_{x=1}^{x_{TOTAL}} \eta_x$$

with η_x is the efficiency of component or function x. Typical (rounded) efficiencies include illumination lens (99%), light integration (90%), PCS (90%), PBS (85%), analyzer (90%), illumination overfill (90%), projection lens (85%). The 'duty cycle' of the light valve, typically a Ferroelectric or Twisted Nematic LCOS must also be included as an additional efficiency factor in color sequential systems [13][14]. Ferro-electric Liquid Crystals have switching times less than 100μs, therefore the duty cycle is much better than TN materials which have also improved significantly over the past years.

3. Single Panel System Alternatives

Disadvantages of the colorswitch architectures are the cost of the complex polarization conversion array and the currently lower efficiency, higher cost (and availability) of the sequential color generation [1] [12], compared to a RGB(W) color wheel.

3.1 Colorwheel System

In Figure 2 a RGB colorwheel is placed after an elliptical lamp and a condensor-lens is used to collimate the light through the integrator plates.

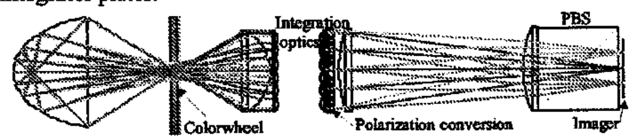

Figure 2. Single panel FLC prototype

The integrator and PCS were designed smaller and therefore less expensive. Using a 0.78" Ferro-Electric Liquid Crystal panel (less than half of the 1.15" panel size of current scrolling prism systems [13]) we achieved a maximum brightness of more than 600 Ansi-lumens, which indicated the potential of single panel projectors for application in consumer products. The glass PBS prism can be replaced by a wire-grid polarizer [8] to reduce artifacts like stress birefringence. The flatness must be controlled sufficiently when the wire-grid is used as a front mirror in the imaging part.

3.2 Polarization Recovery

Disadvantages of integrator lens arrays are the optically poor fillet regions between lens elements and the tolerance requirements for the optical axis of each lens. Integrating rods or tunnels [10] are often used in combination with a colorwheel because they are an inexpensive and compact solution for light integration. The system in Figure 3 integrates the function of a pre-polarizer and polarization conversion.

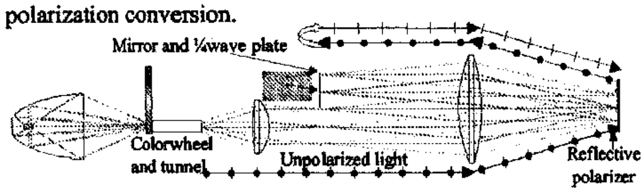

Figure 3. Polarization Recovery System

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A reflective polarizer is placed near the position of the LCD (illumination window image). The first lens, (focal length f1) is placed at a distance ~f1 from the tunnel, making a lamp (pupil) image at a distance ~f1. A second lens (focal length f2) at a distance ~f2 re-images the pupil at infinity for telecentric illumination at the light valve and also images the tunnel exit (rectangular window) at the position of the light valve.

The second lens is de-centered in this example, which causes the illumination at the window to be off-axis, filling half the system's étendue. The wire-grid polarizer transmits one polarization and reflects the other. The light from the reflected polarization state is imaged by the second lens onto a mirror with a ¼ wave film/coating at the position of the lamp (pupil) image.

The polarization direction is rotated and the 'window' is re-imaged back onto the position at the reflective polarizer window that will transmit the recovered polarization state, thereby filling the other half of the system's étendue. The S and P components of the polarization are indicated schematically in Figure 3. The ¼ wave plate may be placed anywhere between the mirror and the reflective polarizer. This method can be used for single panel applications (e.g. transmit light directly through a transmissive panel) or in other one, two and three panel systems by re-imaging the rectangular illumination window.

The Polarization Recovery System doubles the étendue in one direction. In Figure 4 the projection lens pupil is filled more efficiently by tapering the tunnel (ideally like a Compound Parabolic Concentrator) in one direction, e.g. from rectangular to 16:9 aspect ratio, matching the LCD. This makes the lamp image elliptical and increases the pupil fill factor and light collection for a given F#.

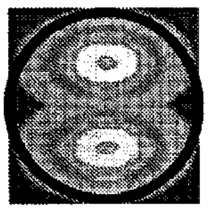

Figure 4. Pupil filling

3.2.1 *Polarization Recovery for LCOS*

The same Polarization Recovery System can theoretically also be applied for a single panel LCOS system with, for example a reflective wire grid PBS as is drawn in Figure 5.

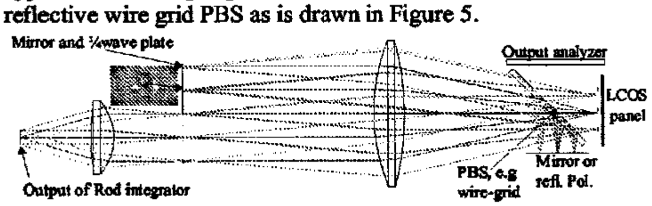

Figure 5. Polarization Recovery System for LCOS.

The light is split at the wire-grid polarizer into S and P polarized light. The reflected S-polarized light is reflected by a mirror (or a second reflective polarizer) to the reflective PBS and then back towards the relay lens that creates an intermediate image of the lamp (pupil) for recycling with a mirror and a ¼λ film.

The wire-grid side is at the side of the LCD for analyzing the light from the panel into the projection lens. An additional analyzer can improve the contrast by absorbing the light leakage from the PBS.

The advantage of systems like this is that the same PBS is used for the polarization conversion and for the imaging/analyzing, which reduces the cost. The currently available wire-grid polarizers have a lower blue efficiency and contrast when they are used as a 45° PBS. This can be improved in the future with a smaller pitch wire-grid pattern [8].

3.2.2 *Polarization Recovery with PBS Prism*

Another PRS variant is shown in Figure 6 where the polarization conversion is done before an imaging PBS with a separate PBS prism. The same principle is applied in terms of imaging the pupil at a mirror with a ¼ wave plate.

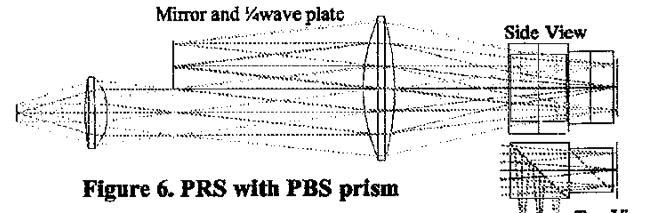

Figure 6. PRS with PBS prism

The S-polarized reflection of the dichroic PBS prism is very efficient (about 98%) as it has a high extinction ratio for the transmission of S-polarized light. The transmission of P-polarized light is lower and shows a higher angular dependency compared to wire-grid polarizers.

We measured the angular characteristics of the PBS coating in this architecture using a conoscope (which measures the transmission as a function of the azimuth and polar angles). The polar plot in figure 7 shows the original coating (left) and an improved coating for transmission and angular dependency. The improvement in the horizontal and vertical direction is also shown in the Figure 7.

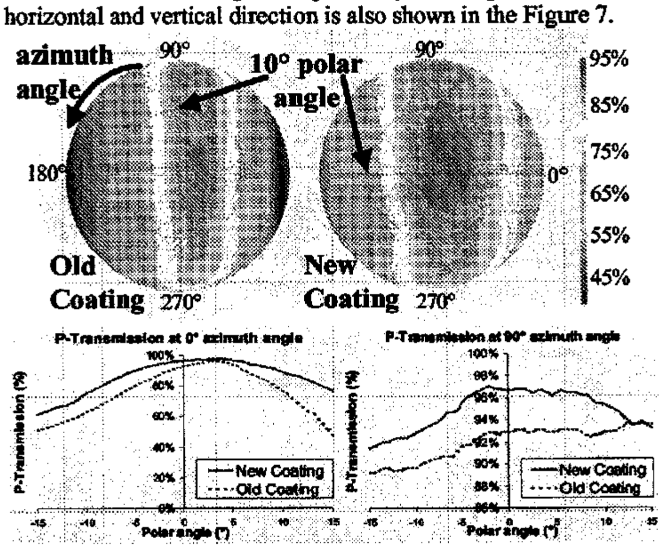

Figure 7. Conoscopic transmission results of PBS prism

We optimized the system performance further by taking into account the angular intensity distribution $I_{illumination}(\theta,\phi)$ of the illumination through the components. This can be measured or modeled in software as ASAP or LightTools.

$$\eta_x = \frac{1}{I_{total}} \int\int I_{\text{illumination}}(\theta,\phi) \cdot T_{\text{optics}}(\theta,\phi) d\theta\, d\phi$$

Since there are two prisms in this system, the system improves according to the square of the prism improvement factor. As shown in figure 4 this general architecture results in two hot spots in the vertical direction. This direction coincides with the high transmission angles of the PBS prism in Figure 7. In combination with the improved transmission of the PBS prism the efficiency of this system is close to the performance with the wire-grid Polarization Recovery System. The efficiency of the described polarization recovery system as a function of the étendue is included in paragraph 5.

4 Integration of Functionality

To simplify the system further we also investigated systems with integration of polarization recovery and a rod or tunnel integrator.

4.1 Integrating Polarization Recycling

Texas Instruments presented their concept of Scrolling Color Recapture, invented by D. Scott Dewald [4][5]. We simulated different polarization recovery systems using a Polarization Recycling Rod (PRR) or Tunnel (PRT) with a reflective polarizer, an input aperture area (A_{mirror}) and a means for rotating the polarization direction such as a ¼ wave plate at the mirror.

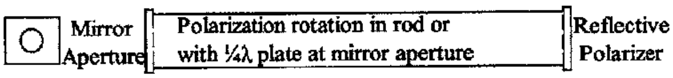

Figure 8. Polarization Recycling Rod

Some methods for manipulating the polarization were discussed by M. Duelli of OCLI [6]. When we analyze a cycle of the polarization recovery path in Figure 8, i.e. the light that is reflected by the exit polarizer and then by the input aperture, back to the output polarizer for a second chance into the system, we find that one polarization conversion light path cycle P_{path} is:

$$P_{path} = R_{p-pol} \cdot T_{\text{int}}{}^2 \cdot (1 - \frac{A_{mirror}}{A_{\text{int}}}) \cdot R_{mirror}$$

where $R_{p\text{-}pol}$ (92%) is the reflection of polarized light, T_{int} (98%) is the transmission of the integrator, R_{mirror} (96%) is the reflection of the mirror and A_{int} is the area of the integrator.

The polarization recovery gain factor G_{pol} (relative to only the efficiency of a reflective polarizer) of the light coupled into the rod aperture is a function of the polarization conversion efficiency γ (up to 90% [6]), defined as the percentage of polarized light that gets rotated by 90° per cycle number (n).

$$G_{pol} = \left(1 + \gamma \cdot \sum_{n=1}^{\infty} \left[(P_{path})^n \cdot (1-\gamma)^{n-1} \right] \right)$$

Using these relationships we can model and optimize the system gain of the Polarization Recycling for a specific lamp (arc) and panel dimension.

$$G_{PRR} = \rho \cdot G_{pol} \quad with \quad \rho = \frac{\tan^{-1}\left(\dfrac{A_{mirror} \cdot \pi \cdot \sin^2(\theta)}{3.8 \cdot d^2 + 0.9 \cdot d - 0.8} \right)}{\tan^{-1}\left(\dfrac{A_{\text{int}} \cdot \pi \cdot \sin^2(\theta)}{3.8 \cdot d^2 + 0.9 \cdot d - 0.8} \right)}$$

Where ρ is the light coupling efficiency of the input aperture and arc d (mm), with system acceptance angle θ, i.e. the light through the mirror aperture relative to the area of the light pipe.

4.2 PRR and sequential color generation

In the system shown in Figure 9 we use a cholesteric BMF (Band Modulation Filter) Color Switch [1] to generate color and to act as a reflective polarizer for polarization recovery. The BMF is placed at the end of an integrating rod with a reflective input aperture. A transmissive color sequential panel is placed at the output of the BMF. This enables a very simple and compact architecture.

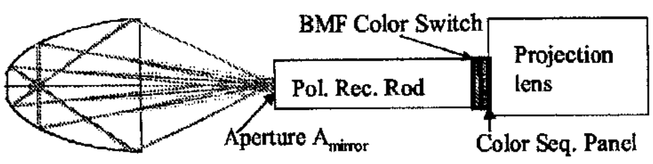

Figure 9. PRR and Cholesteric BMF Color Switch

4.3 PRR and scrolling color recycling

The BMF can be divided into densely packed horizontal segments that can be addressed separately to produce RGB(W) horizontal stripes that scroll downwards (see Figure 10). The addressing speed can be matched to the writing speed of the panel to enable scrolling color. [13]

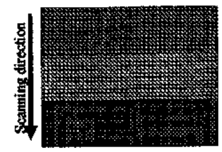

Figure 10. Scrolling color

If two or more colors are present at the BMF we can actually make use of the fact that the cholesteric BMF reflects the unwanted polarized colors, resulting in color recycling as well as polarization recycling in the same unit, significantly increasing the efficiency. Other advantages of the BMF are potential application of dynamic contrast and tunable white color point. In principle the cholesteric filters do not absorb light, but the lifetime with high light intensities and temperatures needs to be proven.

Other ways of combining color recovery and polarization recovery include (switchable) reflective color filters per pixel (like cholesteric BMF structures), or a monolithic SCR colorwheel, which can be imaged onto the scrolling panel. Figure 11 shows a patterned rotating color drum with scrolling horizontal color stripes (like passive cholesteric BMF filters), transmitting one color of one polarization and recycling the rest. This has the advantage of straight scrolling color bars over the display [7][13].

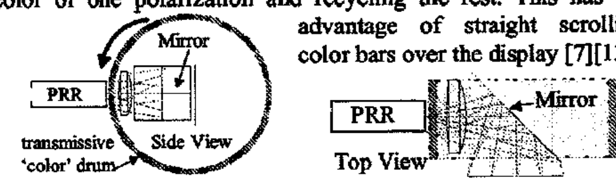

Figure 11. System with Scrolling Color Drum.

The light can be folded out of the drum, which has a relatively large diameter to the tunnel exit to reduce light losses. The stripes can then be imaged onto a light valve for scrolling color.

4.4 Color Recycling Efficiency Calculations

The color recycling gain can be calculated using a similar method as for the polarization recycling. The cycle path of one reflection of the color stripes and from the input aperture is C_{path}:

$$C_{path} = (1 - \frac{A_{colorstripe}}{A_{\text{int}}}) \cdot R_{p-col} \cdot T_{\text{int}}{}^2 \cdot (1 - \frac{A_{mirror}}{A_{\text{int}}}) \cdot R_{mirror}$$

$R_{p\text{-}col}$ (80%) is the reflection of the polarized color back in the rod. The first color recycling term and the unrecycled (Rest) term are:

$$\text{ColRec}_{(n=1)} = C_{path} \cdot (1-\gamma) \ and \ \text{RestCol}_{(n=1)} = C_{path} \cdot (\gamma)$$

From this we can calculate the other color recycling terms with the following recursive function:

$$\text{ColRec}_{(n)} = \text{ColRec}_{(n-1)} \cdot C_{path} \cdot (1-\gamma) + \text{RestCol}_{(n-1)} \cdot P_{path} \cdot \gamma$$

The 'Rest Color' recovery part ($\text{RestCol}_{(n)}$) will be polarization recycled before being color recycled again and is given by

$$\text{RestCol}_{(n)} = (\text{ColRec}_{(n)} - \text{ColRec}_{(n-1)} \cdot C_{path} \cdot (1-\gamma)) \cdot \frac{1-\gamma}{\gamma} + (\text{ColRec}_{(n)} - \text{RestCol}_{(n-1)} \cdot P_{path} \cdot \gamma) \cdot \frac{\gamma}{1-\gamma}$$

From this the color recycling efficiency gain factor (G_{col}) and the total system gain (including PRR function) can be approximated:

$$G_{col} = 1 + C_{path} \cdot (1-\gamma) + \sum_{n=2}^{\infty} \text{ColRec}_{(n)} \ and \ G_{system} = \rho \cdot G_{pol} \cdot G_{col}$$

The graph in figure 12 shows the modeled gain as a function of γ for an input aperture ratio of 0.2. It includes the Polarization Recycling Rod Gain (G_PRR), the Color Recycling Gain (G_CR), the combined gain (G_P*C) and the system gain that includes the coupling efficiency ρ for a 1.15" panel, 1.0 mm arc, $F_{\#}2.4$ system.

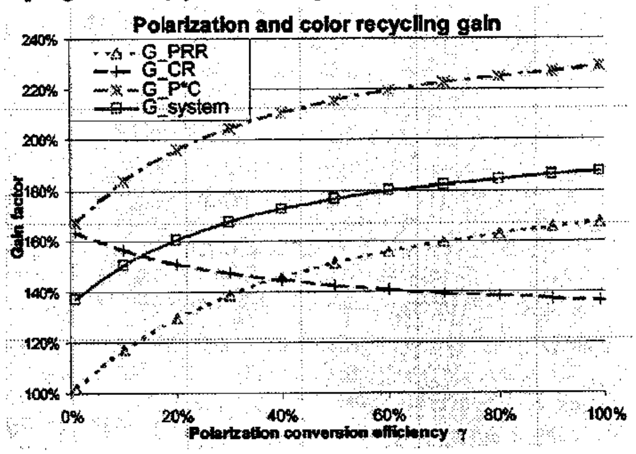

Figure 12. Gain factor as function of γ

The Color Recycling gain reduces with increasing γ. Therefore, the total polarization and color recycling gain has a reduced dependency of γ, which slightly improves spectral performance.

5. Discussion and Conclusions

The cost of single panel color sequential Liquid Crystal projectors is partly driven by the polarization recovery and color generation solutions. We designed and constructed a single 0.78"FLC panel system with >600 lumen, indicating the potential of single panel LC systems for the consumer market.

The graph in Figure 13 shows the optimized polarization and color recovery rod gain (G_P&C) as a function of the étendue, the Polarization Recovery System (G_PRS) of chapter 3.2 and the contribution of the Polarization Recycling Rod gain (G_PRR). The system gain (relative to using a reflective polarizer without polarization recovery) is shown for γ=90% and lamp arcs with 1.0 mm and potential future 0.7 mm arc dimensions.

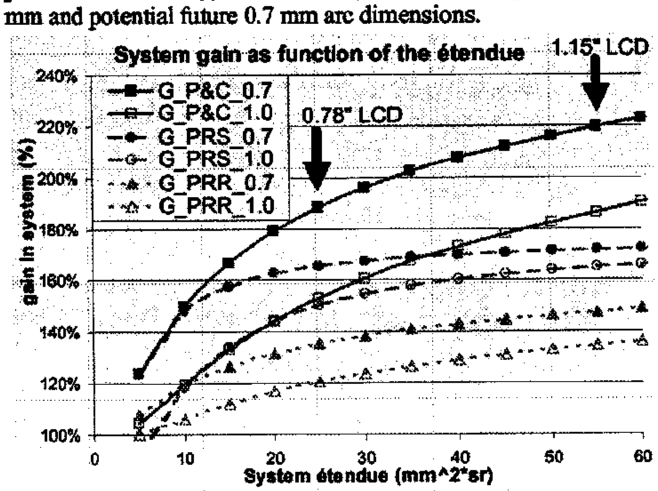

Figure 13. System gain as function of the étendue

The optimum input aperture in the polarization and color recovery rod integrator for a 1.15" panel, 1.0 mm arc lamp, is around 20% and for the 0.78" system around 30% of the integrator area.

The Polarization Recovery Rod seems to be the least expensive system. However, the system gain (20-35%) is (depending on the étendue) only half of the system gain with the novel Polarization Recovery System as described in paragraph 3.2.

Combining the Polarization Recovery Rod with our new Color Recycling solutions increases the benefit of the reflecting input aperture at the rod or tunnel, improving the efficiency of the PRR concept with another 20-35%. Reducing the arc size is more important for this system than for conventional Polarization Recovery Systems.

In order to bring a disruptive projection system on the market, we need further integration, simplification and innovation for cost reduction.

6. Acknowledgements

The author wishes to thank Benny Svardal for his work on the single panel FLC prototype and Markus Duelli for his sample of a polarization recycling rod.

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